

Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet

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An acoustic deterrent system producing 20–600 Hz sound was used to repel estuarine fishes away from a power station cooling water inlet. During sound emission, total fish impingement decreased by 60%. The avoidance response varied among species from no effect to highly efficient deflection. *Lampetra fluviatilis* and Pleuronectiformes were less affected by the sound system while the deflection of clupeoid species was particularly effective. Average intake rates of *Clupea harengus* and *Sprattus sprattus* decreased by 94.7 and 87.9%, respectively. The results were explained as a function of species-specific differences in hearing ability and swimming performance. In general, species without swimbladders showed no or a moderate response while intake rates of species with accessory structures increasing the hearing abilities, such as a swimbladder or a functional connection between the swimbladder and the inner ear, were significantly reduced during test periods.

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Key words: acoustic fish deterrent; *Clupea harengus*; cooling water intake; low frequency sound.

INTRODUCTION

The abstraction of cooling water by power plants causes a wide range of ecological impacts on aquatic communities. Effects are situated both within the cooling-water circuit and in the cooling water receiving water body. Thermal loading related to cooling water discharges directly interferes with physiological processes of the biota, such as enzyme activity, feeding, reproduction, respiration, growth and photosynthesis (Hadderingh *et al.*, 1983). Behavioural changes (attraction or avoidance) are commonly observed in organisms subjected to thermal discharges as well (Kennish, 1992). Of greater potential impact on the aquatic communities than waste heat discharges, however, are the losses of various life-history stages of invertebrates and fishes due to impingement on intake screens or entrainment through cooling systems. It is not uncommon for millions of fishes and crustaceans

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to become impinged on power plant intake screens each year (Kennish, 1992) and many more eggs, plankton and larvae of invertebrates and fishes are killed. The absolute numbers are $>10^{10}$ individuals annually at some power plants (Kennish, 1992). In addition to impingement and entrainment, adverse effects on aquatic organisms may arise from the use of biocides to control fouling organisms.

To reduce the impact of cooling water abstraction on fish populations in the surrounding waters, different methods and devices have been introduced with variable success. The major deflection methods at power stations include visual stimuli (*e.g.* air-bubble screens, lights or strobe lights), water velocity and pressure changes, electrical shocks and sounds. Mechanical exclusion devices use fine-screens surrounding an intake from which cooling water is drawn.

The Doel nuclear power plant (Belgium) withdraws cooling water from the Scheldt Estuary, an important nursery for young-of-the-year marine and fresh-water fish species (Maes *et al.*, 1998). The density of fishes in the cooling water circuit averaged 64 fishes per 1000 m³ in the period between 1991 and 2001, resulting in the loss of *c.* 50 million fishes each year. In addition, a similar number of crabs and shrimps are retained on the filter screens. To reduce the impact of the power plant cooling water inlet on the estuarine fish populations, it was proposed to install and evaluate a fish deflection system based on sounds to guide or deter the fishes away from the cooling water inlet. This proposal was based on two major observations. First, it was assumed that conventional deflection devices based on light stimuli or electrical fields, if installed, were not likely to be efficient due to the high natural turbidity and the salinity of the water. Also mechanical exclusion devices to prevent fishes from entering the intake were considered impractical. Second, trials on site showed that representatives of the Clupeidae (herrings), Osmeridae (smelts) and Cyprinidae (carps) were moderately to extremely sensitive to mechanical contacts and suffered post-intake mortalities that were higher than those for other fish species. The aim was to deter these highly vulnerable fish species.

The objective of this study was to test the efficiency of an acoustic fish deterrent (AFD) system placed at the cooling water intake to avoid fishes entering. Previous studies have used sound in an attempt to influence the movement of fishes near to power plant cooling water intakes or at hydropower facility turbines. These studies, however, have concentrated mainly on American salmonids (Knudsen *et al.*, 1997) and clupeids (Haymes & Patrick, 1986; Ross & Dunning, 1993) and ranged from totally unsuccessful in controlling behaviour, to demonstrating potential usefulness for a few species under certain conditions (Anon., 1995). Few other fish groups have been tested in a systematic way to determine if they would avoid low frequency sound (Anon., 1995). Knudsen *et al.* (1997), however, recognized the need for large-scale field studies to test the true effectiveness of infrasound screens under natural conditions. Accordingly, this paper is one of the few reporting on the avoidance response of an entire fish community to the production of underwater infrasound.

MATERIALS AND METHODS

The Doel nuclear power plant is located on the west bank of the brackish water part of the Scheldt Estuary (51°15' N; 04°17' E) (Maes *et al.*, 1998). Its cooling water intake is

situated 2 m above the bottom and withdraws $25.1 \text{ m}^3 \text{ s}^{-1}$ of water through five intake apertures measuring $4.0 \times 2.4 \text{ m}^2$ each. The intake is located in open water at 50 m off the shore during low tide and 200 m at high tide. Water is transported through a 540 m long pipeline to a communicating reservoir at the site. Here, fishes, crustaceans, plant material and debris are removed from the cooling water by vertical travelling water screens with a square mesh-size of 4 mm and afterwards flushed into a container, the sampling point. The residence time of fishes within the system *i.e.* the time animals spend between the intake point in the river and the sampling point is at least 20 min. Goldfish *Carassius auratus* (L.), measuring between 7 and 23 cm in total length (L_T) were used to estimate more exactly the residence time of fishes by releasing 246 live fish into the cooling water inlet. After 20 min, 69% of the fish were recaptured, after 1 h, 80%.

In 1997, a sound projector array AFD system was designed by Fish Guidance Systems Ltd. (FGS, Southampton, U.K.) and installed near the offshore intake. In total, 20 large FGS Mk II 30–600 sound projectors (600 W each) were installed to create a repellent sound field close to the water intake openings to cause passing fishes to 'veer away'. A multiple signal generator, programmed with eight different sound signals, was used to avoid resident species habituating to any one sound signal. The sounds comprised frequencies within a range of 20–600 Hz repeated every 0.2 s. These were emitted from the sound projectors *via* a flexible neoprene membrane, producing a nominal sound pressure output of 174 dB (reference pressure: $1 \mu\text{Pa}$). The membrane is protected from external damage by a conical grill of concentric rings. Depth compensation is provided by an air reservoir. A preliminary evaluation in 1997–1998 yielded no significant reduction in numbers of fishes entering the intake and the sound projectors were relocated and installed at the intake. After reinstallation, 15 trials were held between October 1998 and October 2001 to evaluate the efficiency of the AFD system (Table I). Each trial lasted 48 h. The AFD system was operating during the first day (24 h) of the trials and was turned off during the second day (24 h). Fishes and crustaceans were collected in nets, identified and counted. Gobies of the genus *Pomatoschistus* were not identified to species level.

A *t*-test for dependent (or paired) samples was performed on the \log_{10} -transformed data to examine the difference in the total catch in numbers observed between control days without sound projection and days with sound projection. Differences were significant at $P < 0.05$. Fifty individuals, caught over the entire test period, were used as the minimum sample size for statistical testing. The reduction *R* in intake numbers was

TABLE I. Sampling dates of the trials and tide-averaged temperature and salinity

Sample number	AFD on	AFD off	Temperature ($^{\circ}\text{C}$)	Salinity
1	26 October 1998	27 October 1998	14.8	7.5
2	9 November 1998	10 November 1998	10.2	1.0
3	23 November 1998	24 November 1998	7.8	1.4
4	7 December 1998	8 December 1998	5.4	1.7
5	15 December 1998	16 December 1998	6.7	1.8
6	12 January 1999	13 January 1999	7.9	1.9
7	2 November 1999	3 November 1999	12.6	11.6
8	1 December 1999	2 December 1999	8.8	9.4
9	26 January 2000	27 January 2000	6.6	1.5
10	10 June 2000	11 June 2000	18.7	9.2
11	29 November 2000	20 November 2000	13.0	5.2
12	19 December 2000	20 December 2000	11.2	2.0
13	28 February 2001	1 March 2001	10.1	0.9
14	26 September 2001	27 September 2001	19.0	7.0
15	23 October 2001	24 October 2001	17.2	3.5

AFD, acoustic fish deterrent.

expressed as a percentage: $R = 100 - 100 n_{\text{on}} n_{\text{off}}^{-1}$, where n_{off} is the total catch of the control samples (sound off) and n_{on} is the total catch of the test samples (sound on).

Additionally, the influence of salinity and temperature on the species-specific efficiency of the AFD system was tested. The contribution of each of these variables on the variation in percentage reduction was assessed using multiple linear regression models. On selected occasions, the L_T (cm) of herring *Clupea harengus* L. and sprat *Sprattus sprattus* (L.) were measured to examine differences in average fish size during test and control periods. The hypothesis of no difference between sound-on and sound-off conditions was tested using one-way ANOVA.

RESULTS

During the survey *c.* 350 thousand fishes were sampled comprising 24 families and 41 species. Gobies were not identified to species level but three species occurred in the screen samples: the marine gobies *Pomatoschistus minutus* (Pallas) and *Pomatoschistus lozanoi* (de Buen) and the estuarine resident *Pomatoschistus microps* (Krøyer). Marine species, both marine estuarine opportunistic species and marine vagrants, dominated the fish fauna in terms of diversity and abundance. Other life cycle categories including freshwater fishes and diadromous species were less abundant.

Total fish impingement decreased by 59.6% during the AFD operation. The overall reduction of fish impingement was mainly due to a reduction in the number of gobies since these species represented 78% of the entire catch. Most species that were available for entrapment by the cooling water intake during the study period, however, decreased their intake numbers. The difference in intake numbers between sound-on and sound-off conditions was significant for nine species or taxa (Table II): herring, sprat, white bream *Abramis bjoerkna* (L.), smelt *Osmerus eperlanus* (L.), bass *Dicentrarchus labrax* (L.), perch *Perca fluviatilis* L., sole *Solea solea* (L.), flounder *Platichthys flesus* (L.) and gobies of the genus *Pomatoschistus* sp. In particular, the deflection of clupeids was successful. For herring, AFD operation resulted in an average catch reduction of 94.7%. In periods of maximum herring abundance in the estuary, >99% were deterred (Fig. 1). Reduction in the number of sprat during test periods averaged 87.9%. White bream was the only cyprinid for which numbers drawn in were significantly reduced but numbers of other representatives of this family were rather low. In Percidae, AFD operation yielded a significant reduction in the catch of perch by 51.2%. Numbers of the pikeperch *Stizostedion lucioperca* (L.) decreased by almost 70% but the reduction was not consistent over the different trials and hence, not significant (Table II). Results for flatfishes varied, with a significant reduction in sole and flounder. The catch of dab *Limanda limanda* (L.) did not vary between the test and control conditions. Pipefishes, sticklebacks and mullets did not show any avoidance reaction to the AFD system (Table II). For all other species including gadoids, numbers were fairly low and no (statistical) conclusions were drawn. Data for these species are therefore not presented.

Multiple regression of temperature and salinity as independent variables and the percentage reduction of the nine species that responded significantly to sound emission as dependent variable did not yield significant models (multiple regression analysis; $n = 15$; $P > 0.05$). Temperature and salinity modify the speed

TABLE II. Percentage reduction in the total catch of fishes impinged by the cooling water intake of the Doel nuclear power plant during the experiments. The total catch (sum) and the daily mean \pm s.e. sample size and ($n=15$) are given for test periods (AFD on) and for control periods (AFD off). Fish species are subdivided into a group with significant reductions during sound projection (t -test for dependent samples; $n=15$; $P<0.05$) and a group with statistically insignificant reductions (t -test for dependent samples; $n=15$; $P>0.05$). Data for species of which <50 individuals were caught during the trials are not given

Species	%	AFD on		AFD off	
Significant reductions					
		Sum	Mean \pm s.e.	Sum	Mean \pm s.e.
<i>Clupea harengus</i>	94.7	2095	139.7 \pm 49.2	39 893	2659.5 \pm 748.7
<i>Sprattus sprattus</i>	87.9	4298	286.5 \pm 83.1	35 647	2376.5 \pm 672.6
<i>Dicentrarchus labrax</i>	75.6	447	29.8 \pm 7.4	1831	122.1 \pm 26.4
<i>Osmerus eperlanus</i>	53.5	260	17.3 \pm 12.4	559	37.3 \pm 25.6
<i>Perca fluviatilis</i>	51.2	168	11.2 \pm 4.8	344	22.9 \pm 9.3
<i>Solea solea</i>	46.6	86	5.7 \pm 4.7	161	10.7 \pm 7.6
<i>Pomatoschistus sp.</i>	46.1	91 652	6110.1 \pm 2715.4	169 938	11 329.2 \pm 4694.1
<i>Abramis bjoerkna</i>	40.1	82	5.5 \pm 4.0	137	9.1 \pm 3.7
<i>Platichthys flesus</i>	37.7	129	8.6 \pm 6.0	207	13.8 \pm 9.3
Insignificant reductions					
<i>Liza ramada</i>	75.8	109	7.3 \pm 2.2	450	30.0 \pm 17.1
<i>Stizostedion lucioperca</i>	69.8	74	4.9 \pm 2.0	245	16.3 \pm 9.3
<i>Syngnathus rostellatus</i>	43.3	394	26.3 \pm 17.4	695	46.3 \pm 45.6
<i>Anguilla anguilla</i>	37.3	141	9.4 \pm 3.0	225	15.0 \pm 5.1
<i>Pungitius pungitius</i>	7.1	195	13.0 \pm 4.2	210	14.0 \pm 4.7
<i>Lampetra fluviatilis</i>	5.9	32	2.1 \pm 1.4	34	2.3 \pm 1.2
<i>Gasterosteus aculeatus</i>	1.4	1542	102.8 \pm 32.1	1564	104.3 \pm 32.4
<i>Limanda limanda</i>	0.0	111	7.4 \pm 7.4	111	7.4 \pm 6.5

AFD, acoustic fish deterrent.

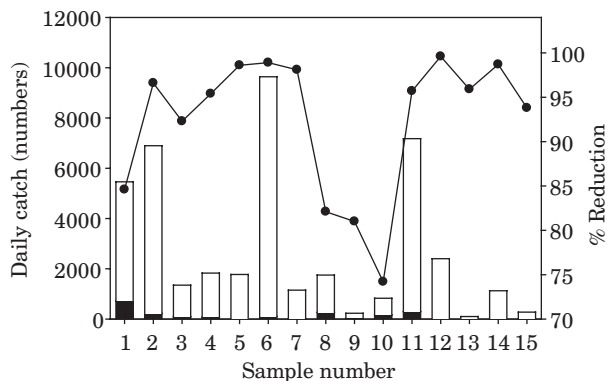


FIG. 1. Numbers and reduction (●) in the daily catch of herring during sound emission (AFD on, ■) and during controls (AFD off, □). Dates corresponding to the sample numbers are given in Table I.

TABLE III. Difference in total length in herring and sprat during sound emission (AFD on) and during the control period (AFD off). Differences in L_T were tested for statistical significance using one-way ANOVA on two groups. Values for the number of observations (n) and the probability level are also given

Species Date	AFD on L_T (cm)	AFD off L_T (cm)	n	P
<i>Clupea harengus</i>				
2 Feb 1999	8.2	8.6	269	<0.01
1 Dec 1999	8.2	8.3	194	>0.05
26 Jan 2000	8.0	8.4	152	>0.05
<i>Sprattus sprattus</i>				
2 Nov 1999	6.5	6.7	234	<0.05
1 Dec 1999	6.4	6.7	126	<0.05
26 Jan 2000	6.4	6.5	174	>0.05

AFD, acoustic fish deterrent.

of sound through water. It can thus be expected that the shape of the sound field near the intake will also undergo some modifications with changing salinity and temperature but the modifications are not of such extent that they influence the sound system's efficiency.

Analysis of L_T data was performed on herring and sprat (Table III). The average size of both species decreased during sound emission but this decrease was limited to a few mm.

DISCUSSION

Artificial sounds have previously been used to reduce fish impingement by power plant intakes or turbines. Infrasound (10 Hz) produced flight and avoidance responses in Pacific juvenile salmonids (Knudsen *et al.*, 1997). Haymes & Patrick (1986) used low-frequency sound to frighten alewives *Alosa pseudoharengus* (Wilson) away from an experimental structure. They reported a reduction of between 71 and 99%. Clupeids can also detect ultrasound (Mann *et al.*, 1997) and high frequency sounds have been applied to reduce the catch of alewives at a power plant on Lake Ontario (Ross & Dunning, 1993). The present results clearly demonstrate that an AFD system producing low frequency sounds between 20 and 600 Hz can repel many fish species at an estuarine cooling water intake. The response to sounds and the associated reduction in numbers captured by the intake, however, appeared to be species-specific, varying from no effect to highly efficient deflection. The difference between species in intake rates between test conditions and control samples is attributed to species-specific differences in both sound detection, appropriate response and swimming performance.

Different avoidance reactions of species to the sound system are due to differences in hearing abilities, and in particular, to differences in auxiliary anatomic structures that improve the sensitivity to sound (Hawkins, 1986;

Helfman *et al.*, 1997; Popper & Lu, 2000). Sound propagates rapidly and efficiently through water. Sound sources set up a wave that travels through the water. The wave can be characterized at a particular point by the particle velocity, a 'to-and-fro' motion of the component particles, and the sound pressure, a variation in pressure above and below the ambient level. The 'to-and-fro' displacements that constitute sound are extremely small, of the order of nanometres (Hawkins, 1986). The motion of particles is detected in the inner ear.

Species with swimbladders, although not all, exhibited a clear avoidance behaviour to the AFD system as their intake numbers during sound emission significantly decreased. Significant results were obtained for the smelt and various acanthopterygian taxa (*e.g.* gobies, perch, sea bass and sand smelt). In gadoids, the swimbladder is positioned closely to the inner ear, which makes gadoids sensitive to sounds. Trials of a similar AFD system at Hartlepool power station (Tees Estuary, U.K.) confirmed that gadoids were deflected effectively as the catch of whiting *Merlangius merlangus* (L.), which ranked third in cooling water samples, decreased by 53.5% (A.W.H. Turnpenny, J.M. Fleming, K.P. Thatcher & R. Wood, pers. comm.). At Doel, the contribution of gadoids to the annual catch is marginal, although 0+ and 1+ year whiting and cod *Gadus morhua* L. captures peak during November and December in fyke nets at a nearby mudflat (Maes *et al.*, 1997). During the present study, only 13 whiting were caught of which 10 were captured during 'sound off' conditions. Some species, although having a swimbladder, remained unaffected by the sound system. Representatives of the Gasterosteiformes (pipefishes and sticklebacks) have armoured bodies consisting of dermal plates that possibly decrease the effect of sound pressure waves on both the inner ear and the swimbladder.

Small movements of the swimbladder due to sounds can be transmitted to the inner ear directly through the tissue but also *via* anatomical structures. Such structures considerably increase the hearing abilities in fishes. Herring, sprat and anchovy *Engraulis encrassicolus* (L.) (Clupeiformes) have thin, hollow ducts extending anteriorly from the swimbladder that expand into gas-filled bullae in the inner ear (Helfman *et al.*, 1997). This connection increases the sensitivity of clupeoids to sound and explains the high avoidance reaction in herring and sprat to the acoustic deterrence system. In ostariophysan fishes such as the cyprinids, weberian ossicles connect the swimbladder to the perilymph of the inner ear resulting, again, in increased sensitivity for low frequency vibrations. White bream, however, was the only cyprinid to be significantly deflected by the system whilst other cyprinids showed no reaction or occurred in low numbers. In contrast to the present results, impingement rates of cyprinids at a river pumping station in York, England, were significantly reduced by 80% when sounds were produced to deter fishes (A.W.H. Turnpenny, J.M. Fleming, K.P. Thatcher & R. Wood, pers. comm.).

The presence of hearing-related modifications does not appear to guarantee successful deflection. Considerable differences in the reduction occurred amongst species with high sensitivity to sound that could not be explained as a function of their hearing abilities alone. Such fishes may well detect the AFD sounds, but if the current velocity towards the intake exceeds the maximum swimming speed, they cannot necessarily escape and become impinged. This is

particularly true at cooling water intakes in estuaries where strong tidal currents probably prevent fishes of perceiving a current towards the intake unless they are nearly on the intake. The average current velocity of the river, caused by the tides, is 0.65 m s^{-1} . Given the surface area of the intake aperture and the cooling water flow and using hydrodynamics equations, model results (unpubl. data) show that the current velocity towards the cooling water inlet due to cooling water abstraction is 0.52 m s^{-1} upon the intake itself and rapidly decreases to a few cm s^{-1} at 10 m off the intake (unpubl. data). If fishes detect the intake by entering the sound field, they can react by swimming away against the tidal current, and eventually also against the intake current. Based on swimming performance, it is argued that larger-sized individuals and species have a better chance to avoid capture than small-sized species and larval or juvenile life-history stages. This is supported by observations of smaller-sized herring and sprat in the samples taken when the AFD system was operating. Additionally, species with carangiform locomotion using trunk and tail have considerably higher maximum swimming speeds than species with an anguilliform type of locomotion or species using only fins for propulsion. Consequently, fishes with moderate to slow maximum swimming speeds such as eel *Anguilla anguilla* (L.) as well as small-sized life-history stages of goby species may still be impinged in reasonable numbers although it can be assumed that they are well able to detect sounds.

The reliability of extrapolating these results to other power station cooling water intakes seems relevant. Trials of the same system at the Hartlepool power station resulted in similar results as reported in this paper. The highest effectiveness was for clupeids (60–80%). The intake rate of other species possessing a swimbladder was lower (54%) while the catch of non-swimbladder species was reduced by only 16% (A.W.H. Turnpenny, J.M. Fleming, K.P. Thatcher & R. Wood, pers. comm.). It should be kept in mind, however, that the overall reduction rate will probably depend on local conditions as well, such as cooling water entrance speeds, background noise and ichthyofaunal composition of the surrounding waters.

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